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Physics Procedia 3 (2010) 1335–1339

Physics Procedia

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14th International Conference on Narrow Gap Semiconductors and Systems

InSb films grown on the V-grooved Si(001) substrate with InSb bi-layer

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Abstract

V-shaped grooves were prepared by patterning of line and space (LS) using photolithography and Reactive Ion Etching (RIE), and anisotropic etching using hot KOH solution on the patterned 100nm-SiO_2/Si(001) substrate. The V-shaped grooves consist of two <111> planes. The width of grooves was varied from 1 to 10 μm while keeping intervals (line-shaped spaces) between the grooves. The InSb bi-layer was prepared onto the <111> surfaces and the heteroepitaxial growth of InSb films was performed using two-step growth procedure via the InSb bi-layer. Compared with the samples directly grown on the V-grooved Si(001) substrate, the samples grown via the InSb bi-layer showed higher crystal quality. The weak InSb(004) peak was observed in the $2\theta/\omega$ scan at $\chi=0^{o}$, indicating the <001> planes of the InSb films don't face toward to the normal direction of Si(001) substrate. This means that the InSb films grown via InSb bi-layer rotate by 30^{o} with respect to the <111> surfaces of the V-shaped grooves. The confirmation of the rotated InSb(111) peak was difficult, because the incident and diffracted X-ray were obstructed by the grooves. The full width at half maximum (FWHM) of the InSb(111) peak in the $2\theta/\omega$ scan at $\chi=54.7^{o}$ became broader with decrease in the space width between the line-shaped <001> surfaces. This may be related to the areal ratio of the line-shaped <001> surfaces, on which the InSb bi-layer don't form under the present growth condition.

Keywords : Molecular beam epitaxy, V-shaped grooves, Indium Antimonide, bi-layer, Si(001), heteroepitaxial growth

1. Introduction

Recently, InSb has attracted much interest as a candidate material for ultra-high speed and very low power device application [1], because of its high electron mobility of about 78,000 cm^2/Vs at RT and saturation velocity of $5x10^7$ m/s. The heteroepitaxial growth of InSb on Si is important from viewpoint of the integration of InSb-based devices and Si-LSI. However, it is very difficult to achieve due to the large lattice mismatch of about 19.3% between InSb and Si. The other materials such as GaAs have often been used as buffer layer to solve this difficulty [1-3].

We have reported the heteroepitaxial growth of 30°-rotated InSb films on Si(111) substrate via InSb bi-layer [4-6]. The InSb films grown via the InSb bi-layer have good crystal quality and electrical properties. In this case, the

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doi:10.1016/j.phpro.2010.01.187

large lattice mismatch between InSb and Si nominally decreases to about 3.3%. However, the formation of anti-phase domains is not reduced by our growth method. The sample grown via the InSb bi-layer, which was prepared using Si(111)-√7x√3-In surface reconstruction showed high electron mobility of about 20,000 cm^2/Vs at RT [6]. However, our growth method is difficult to apply to the Si(001) surface, because of lack of suitable surface reconstruction to prepare the InSb bi-layer.

One of the solution to apply our growth method to the Si(001) surface may be the formation of the <111> surfaces (V-grooves) onto Si(001) surface by anisotropic etching with KOH solution. We have reported the heteroepitaxial growth of InSb films on V-grooved Si(001) substrate [7]. In this case, the InSb films grew heteroepitaxially on the <111> surfaces, and the <001> planes of the InSb films faced toward the normal direction of Si(001) substrate. However, this InSb films directly grown on the V-grooved Si(001) substrate have poor electrical properties. If our growth method could be applied on the <111> surfaces, high quality InSb films may be grown on Si(001) substrate via the InSb bi-layer. In this paper, we compare InSb films grown on V-grooved Si(001) substrate with and without the InSb bi-layer.

2. Experimental

A molecular beam epitaxy (MBE) chamber with a base pressure of about $2x10^{-8}$ Pa was used for all the deposition. The substrate with a dimensions of about 5 x 13 x 0.6 mm^3 was cut from a p-type Si(001) substrate with 100nm-thick SiO_2 film. The V-shaped grooves were prepared by following procedures. First, the line and space (LS) structure along the <110> direction was patterned on 100nm-SiO_2/Si(001) substrate using photolithography and reactive ion etching (RIE). The patterned substrates were then immersed into hot (115 °C) KOH solution to form V-shaped grooves by anisotropic etching. The space width of LS patterns was varied from 1 to 10 μm. The line width of SiO_2 layer of all samples was fixed to 1μm. This means that a small area of Si(001) surface remains on the substrate. Prior to loading the patterned substrates into the chamber, they were dipped into the HF solution to remove the line-shaped SiO_2 layer. Then they were flash annealed at 1250 °C for 20 min in the vacuum chamber to obtain the clean 7x7 surface on the <111> surfaces. High purity (6N) elemental indium (In) and antimony (Sb) were used as source materials and evaporated from each cell. The substrate temperature (Ts) was monitored by an infrared pyrometer. Before the growth of InSb films, the InSb bi-layer was prepared by following procedure. 0.57 monolayer (ML)-In atoms were deposited at 450 °C on the clean 7x7 surface to make Si(111)-√3x√3-In surface reconstruction. After cooling down the Ts to RT, the √7x√3-In surface reconstruction was prepared by adsorption of additional In atoms of about 1.5ML (total In coverage : 2.07ML) onto the √3x√3-In surface reconstruction. Then 1.73ML-Sb atoms were evaporated at 180 °C onto the √7x√3-In surface reconstruction to prepare the InSb bi-layer. The amounts of In and Sb atoms in this study were different from that reported before [4-6] to prepare the InSb bi-layer onto the V-shaped <111> planes, which tilted by 54.7 ° with respect to the normal direction of Si(001) substrate. The first layer of InSb was deposited at 200 °C for 5 min. The second layer was then deposited at 420 °C. The total film thickness was about 0.7 μm. As mentioned above, the line-shaped <001> surface exists on the Si(001) substrate. To confirm the effect of the <001> plane, the sample grown on the flat Si(001) substrate using the same growth condition was also prepared. The grown samples were characterized by X-ray diffraction (XRD)

3. Results and Discussions

Figure 1 shows the XRD (χ=0°) patterns of InSb films grown on the V-grooved Si(001) substrate via the InSb bi-layer. Here, χ axis is perpendicular to the ω axis, and parallel to incident direction of X-ray at ω=0°. In this case, the crystal orientation of the films to the growth direction is shown in these patterns. The width of the V-grooves (Spaces) is (a) 10 μm, (b) 2 μm, (c) 1 μm, respectively. The areal ratios of the line-shaped <001> surfaces on the surface of these samples are 9.1%, 33% and 50%, respectively. For comparison purpose, the XRD pattern of the sample grown on the flat Si(001) substrate is shown in Fig. 1(d). As shown in Fig. 1(d), the InSb film grown on flat Si(001) substrate shows some InSb related peaks, indicating polycrystalline nature. This means that the deposited In and Sb atoms prior to the first step growth doesn't work well for the heteroepitaxy of InSb on Si(001) substrate. The samples with a surface of 30% or more covered in <001> planes also showed its polycrystalline nature. However, the intensity of many InSb related peaks are decreased with decrease in the areal ratio of the <001> surfaces. In the sample grown on the V-grooved Si(001) substrate with 10μm space width, very weak InSb(004) peak is only showed in the pattern, as shown in Fig.1(a). In the case of the direct growth of InSb films grown on the V-grooved

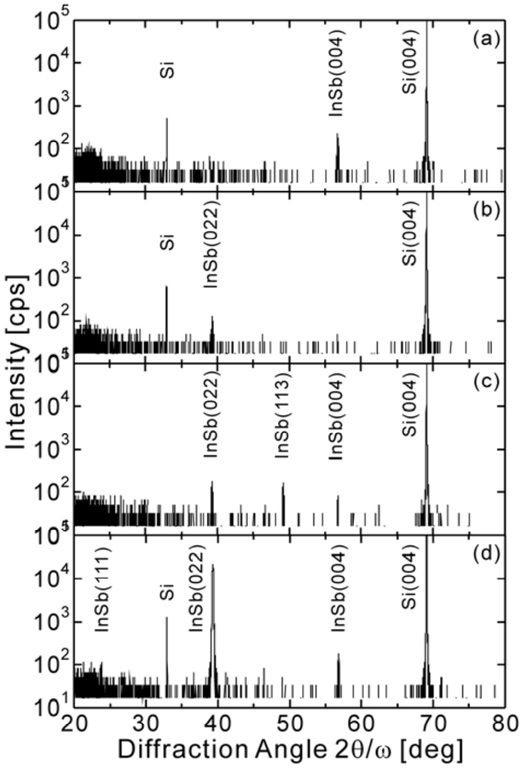

Fig. 1 XRD (χ=0^o) patterns of InSb films grown via the InSb bi-layer on Si(001) with V-shaped grooves with space width of (a) 10μm (b) 2μm, (c) 1μm and (d) 0μm (flat), respectively.

Si(001) substrate, the <001> planes of the InSb film face toward to the normal direction of Si(001) substrate. However, in present case, the <001> planes of the InSb film doesn't face toward to the normal direction of Si(001) substrate, because the InSb films grown on Si(111) via the InSb bi-layer rotate by 30^o with respect to Si substrate [4-6]. So, we measured the XRD (χ=54.7^o) patterns of the InSb films to check the crystal quality of the InSb films on the <111> surfaces of V-shaped grooves.

The XRD (χ=54.7^o) patterns of the InSb films grown on the V-shaped grooves via the InSb bi-layer are shown in Fig.2. The space width of the samples is (a) 10μm, (b) 2μm and (c) 1μm, respectively. For comparison purpose, the XRD pattern of the InSb film directly grown on the V-grooved Si(001) substrate with 10μm space width is shown in Fig. 2(d). This sample directly grown on the V-grooved Si(001) showed the intense InSb(004) peak in the 2θ/ω scan pattern (χ=0^o). As shown in Fig.2(a)-(c), the XRD patterns shows only two InSb peaks related to <111> and <333> planes as same as that in Fig.2(d), indicating epitaxy of the InSb film on the V-shaped <111> surfaces. The FWHM of the InSb(111) peak is narrower than that of the sample directly grown on the V-grooved Si(001) substrate. However, the FWHM of the InSb(111) and InSb(333) peaks is getting wider with decrease in the space width, especially InSb(333) peak. The cause of broadening is not clear, but the similar results on the FWHM of the InSb peak were observed in the samples directly grown on the V-grooved Si(001) substrate [7]. This may be related to the line-shaped <001> surfaces.

These XRD results indicate that the quality InSb films are heteroepitaxially grown on the V-shaped grooves via the InSb bi-layer. This also implies that the InSb bi-layer can be applied to the <111> surfaces of the V-shaped grooves. The weak InSb(004) peaks in Fig.1 originate from the 30^o rotation of the InSb film with respect to the <111> surfaces of the grooves. A lot of InSb related peaks in Fig.1 also come from the InSb crystals grown on the line-shaped <001> surfaces. Rao et al. have reported the heteroepitaxial growth of InSb films using Si(001)-4x3-In surface reconstruction [8]. In this case, the heteroepitaxy of the InSb films can be realized at temperatures lower than 300 ^{o}C, because Sb atoms replace the Si-In bonds and form a disordered surface at above 300 ^{o}C. In the present growth condition, the Si(001)-4x3-In surface reconstruction can be formed by deposition of 0.57ML-In at 450 ^{o}C, and the first layer is grown below 300 ^{o}C. However, the XRD patterns in Fig.1 may imply that the 4x3-In surface reconstruction wasn't formed on the line-shaped <001> surfaces under the present growth condition for the InSb bi-layer.

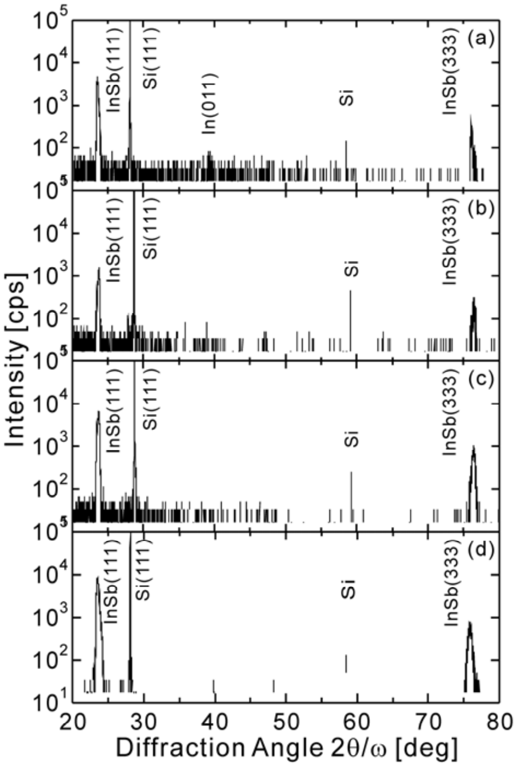

Fig. 2 XRD (χ=54.7^o) patterns of InSb films grown via the InSb bi-layer on Si(001) with V-shaped grooves with space width of (a) 10μm (b) 2μm, (c) 1μm, and of (d) without the InSb bi-layer with V-shaped grooves with space width of 10μm.

To confirm the 30^o rotation of the InSb films on the V-shaped <111> surfaces, we tried to measure the phi scan pattern of the InSb film grown on the V-grooved Si(001) substrate with the InSb bi-layer. However, it was difficult to detect the rotated InSb(001) peaks of the films grown on the <111> surfaces of the grooves, because the incident and diffracted X-ray was obstructed by the grooves .

4. Conclusions

The growth of InSb films on the V-grooved Si(001) substrate via the InSb bi-layer was studied. The space width was varied from 1 to 10μm while keeping the line-shaped <001> surfaces between spaces to 1μm. Because the InSb films rotate by 30^o with respect to the Si in the case of the growth via the InSb bi-layer, the 2θ/ω scan patterns at χ=0^o don't show the intense InSb(004) peak. The FWHM of the InSb(111) peak of the samples grown via the InSb bi-layer became narrower than that directly grown on the V-grooved Si(001) substrate. This means that the growth using the InSb bi-layer can be applied to the <111> surface of the V-shaped grooves.

Acknowledgements

A part of this work is financially supported by Hitachi Kokusai Electric Inc. and a Grant-in-Aid Scientific Research (19760233) of the Ministry of Education, Culture, Sports, Science and Technology, Japan.

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